

The Snowmass Energy Frontier Activities

BNL Snowmass Retreat Day

December 17, 2021

[Alessandro Tricoli \(BNL\)](#)

Our vision for the future of the Energy Frontier

We are in an exciting and pivotal time for the future of HEP

- LHC **Run 2** is providing a wealth of new measurements.
- We have entered the era of **precision Higgs physics**.
- The **HL-LHC** is becoming a reality.
- **We have updated scenario of proposed future colliders.**
- Exciting results from other frontiers: rare processes, cosmology, ...

...and we have no preferred way beyond the SM:

⇒ Great time to **propose new ideas, new perspectives, new tools.**

Our vision for the future of the Energy Frontier

- **The Energy Frontier (EF) group at Snowmass will explore the TeV energy scale and beyond**, under different future accelerator scenarios, including lepton-lepton, hadron-hadron, and lepton-hadron colliders.
- **Sharp physics questions will bring focus to issues pertaining to EF future directions**
 - *Re-evaluate existing ideas* and emphasize how existing work can lead to new ideas
 - HL-LHC results will shape future colliders
 - Identify *new ideas*
 - Highlight “*scientific merit*” of *various collider options* and *connections with other Frontiers*

2020 EF Workshops and Meetings:

- Energy Frontier Kick-off Meeting on May 21, 2020, [see agenda](#)
- Big Picture questions were discussed in the Panel: “*The importance of the Energy Frontier in the US HEP future planning*” at the “[Energy Frontier Workshop - Open Questions and New Ideas](#)”, July 20-22, 2020 ([Zoom recording of Panel Discussion](#))
- Community Planning Meeting, Oct. 5-8, 2020, [see agenda](#)
- Several Topical Meetings and Workshops, [see indico pages](#)

Energy Frontier Restart in 2021

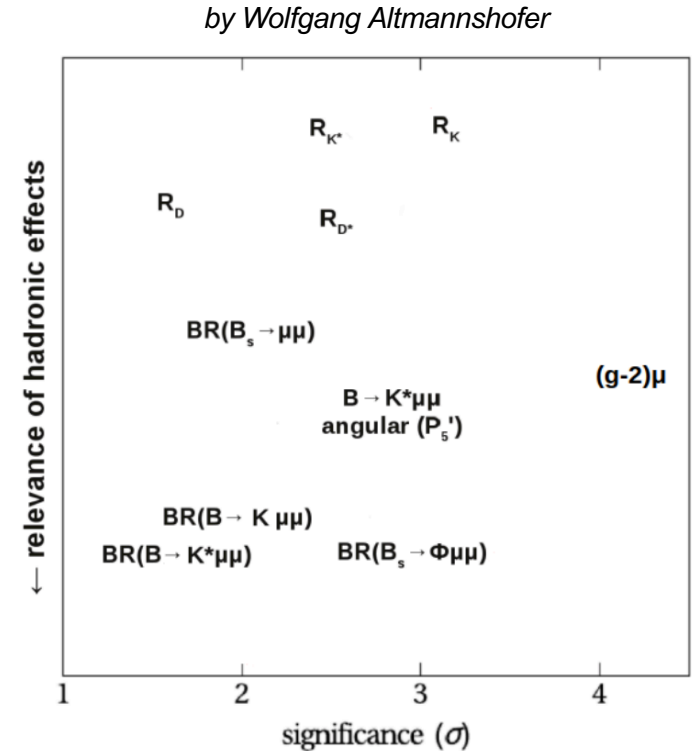
- **Snowmass reports delayed to 2022 due to ongoing COVID-19 pandemic** ([announcement](#))
- **EF slowed down its activities from Jan 2021 until end of June 2021**
 - Community continued to work collaboratively
 - Monte Carlo production activities continued to support the needs of EF
 - Occasional and informal Topical Group 'conversations' to assure scientific continuity and support of ongoing activities

- **Restart of Activity - EF Community Workshop, Aug.30-Sept.3 2021, [agenda](#):**
 - Regroup after the few months of slowdown/pause of Snowmass activities
 - Assess progress made so far
 - Share new studies that started in the meantime
 - Identify gaps in our strategies
 - Update the community with schedule, goals and plans for the upcoming months towards the final reports in summer 2022

→ A week of interesting plenary and parallel sessions, with open discussions on various topics
- **Snowmass Day, Sept. 24, 2021: [agenda](#)**
 - Early Career (EC) as EF speakers: they provided their own perspective and highlight EC studies
- **Topical group meetings have restarted, on biweekly/monthly basis**

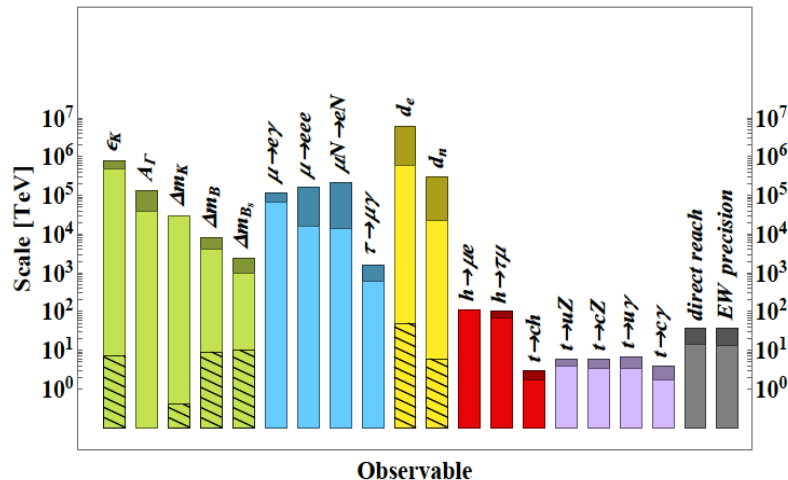
A fast changing landscape

- Physics landscape has been changing since we started Snowmass (a year ago)
- Do we have evidence of the breaking of the SM paradigm in the lepton flavor sector?
- How can we probe (directly or indirectly) the underlying flavor structure of the SM ?



Probing the energy scale for new physics

Probing the energy scale for new physics



Reach in new physics scale from generic dim. 6 operators

Complementarity with other Frontiers

While slow at the start, the energy frontier is ultimately needed to “win the race”

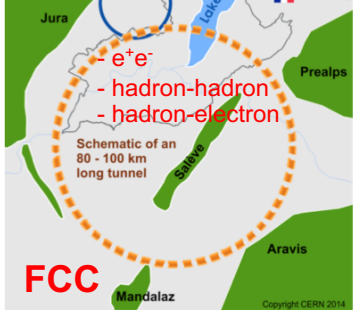


Nevertheless if we get indirect hints from existing or planned experiments its important to know how to test them!

Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

- **Unique complementarity** between electroweak precision fits and flavor observables.
- **Collider reach much broader:** colliders needed to test models across the spectrum of all collider observables

Which machines?



Hadrons

- large mass reach \Rightarrow exploration?
- ▶ $S/B \sim 10^{-10}$ (w/o trigger)
- $S/B \sim 0.1$ (w/ trigger)
- requires multiple detectors (w/ optimized design)
- ▶ only pdf access to \sqrt{s}
- \Rightarrow couplings to quarks and gluons

Circular

- higher luminosity
- several interaction points
- precise E-beam measurement (~ 0.1 MeV) via resonant depolarization)
- ▶ \sqrt{s} limited by synchrotron radiation

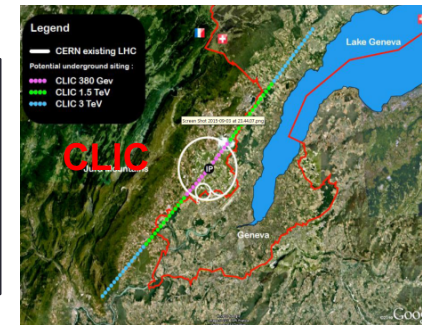
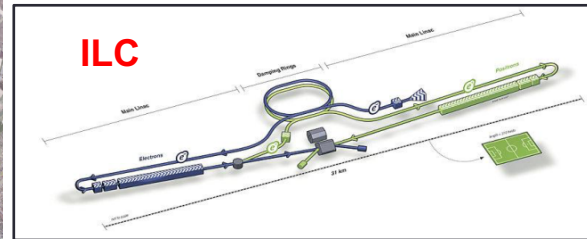
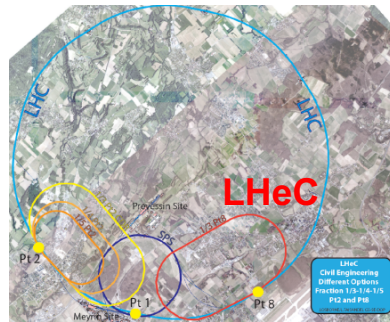
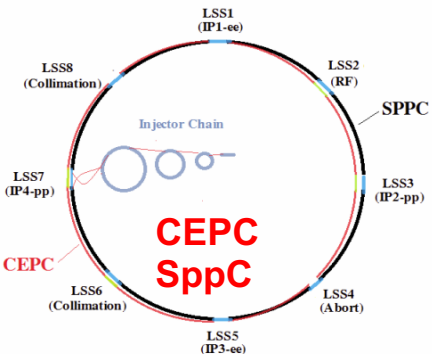
Leptons

- $S/B \sim 1 \Rightarrow$ measurement?
- polarized beams (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- \Rightarrow EW couplings

Linear

- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- ▶ large beamstrahlung
- ▶ one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders
Christophe Grojean Future Measurements 9 Inst. Pascal, Dec. 4, 2019



○ gamma-gamma colliders?

Accelerator Benchmark Parameters

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	\sqrt{s}	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV	$\pm 80/\pm 30$	2
		350 GeV	$\pm 80/\pm 30$	0.2
		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
		1.5 TeV	$\pm 80/0$	2.5
		3.0 TeV	$\pm 80/0$	5
CEPC	ee	M_Z		16
		$2M_W$		2.6
		240 GeV		5.6
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2 M_{top}$		1.5

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	\sqrt{s}	P [%] e^-/e^+	L_{int} ab^{-1}
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh	ep	3.5 TeV		2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10
		14 TeV		20
		30 TeV		90

Note for muon-collider: It is important to note that the plan is not to run subsequently at the various c.o.m etc. These are reference points to explore and assess the physics potential and technology. The luminosity can be varied to determine how best to exploit the physics potential.

Other options to explore:

- Very high energy e+e- collider
- Other emerging ideas:, e.g. $\gamma\text{-}\gamma$ collider, and the C³ e⁺e⁻ collider [C³=Cool Copper Collider]

New

- **Snowmass Agora on Future Colliders:** series of events to enable discussions on physics and feasibility of future collider options (physics potential, technology challenges and R&D, synergies, time frame and costs)
- **One event per month - Dec. 2021-April 2022**

1. Linear e+e- colliders, Dec 15 (<https://indico.fnal.gov/event/52161/>)
2. Circular e+e- colliders
3. Muon colliders
4. Circular pp and ep Advanced colliders

The Energy Frontier Group (I)

- **EF Convenors:** *Laura Reina* (FSU), *Meenakshi Narain* (Brown U.), *Alessandro Tricoli* (BNL)
- **Ten Topical Groups (TGs):**

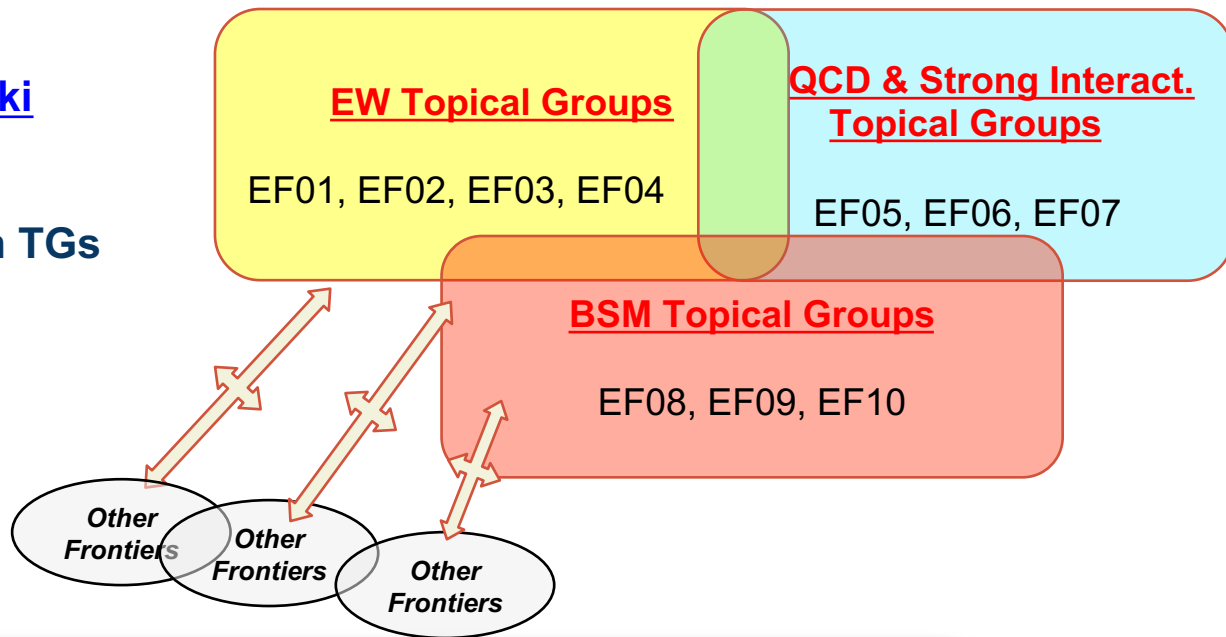
BNL Leadership

Topical Group	Co-Conveners
EF01: EW Physics: Higgs Boson properties and couplings	<i>Sally Dawson</i> (BNL), <i>Andrey Korytov</i> (U Florida), <i>Caterina Vernieri</i> (SLAC)
EF02: EW Physics: Higgs Boson as a portal to new physics	<i>Patrick Meade</i> (Stony Brook), <i>Isobel Ojalvo</i> (Princeton)
EF03: EW Physics: Heavy flavor and top quark physics	<i>Reinhard Schwienhorst</i> (MSU), <i>Doreen Wackerroth</i> (Buffalo)
EF04: EW Physics: EW Precision Physics and constraining new physics	<i>Alberto Belloni</i> (Maryland), <i>Ayres Freitas</i> (Pittsburgh), <i>Junping Tian</i> (Tokyo)
EF05: QCD and strong interactions: Precision QCD	<i>Michael Begel</i> (BNL), <i>Stefan Hoeche</i> (FNAL), <i>Michael Schmitt</i> (Northwestern)
EF06: QCD and strong interactions: Hadronic structure and forward QCD	<i>Huey-Wen Lin</i> (MSU), <i>Pavel Nadolsky</i> (SMU), <i>Christophe Royon</i> (Kansas)
EF07: QCD and strong interactions: Heavy Ions	<i>Yen-Jie Lee</i> (MIT), <i>Swagato Mukherjee</i> (BNL)
EF08: BSM: Model specific explorations	<i>Jim Hirschauer</i> (FNAL), <i>Elliot Lipeles</i> (UPenn), <i>Nausheen Shah</i> (Wayne State)
EF09: BSM: More general explorations	<i>Tulika Bose</i> (U Wisconsin), <i>Zhen Liu</i> (Maryland), <i>Simone Pagan-Griso</i> (LBL)
EF10: BSM: Dark Matter at colliders	<i>Caterina Doglioni</i> (Lund), <i>LianTao Wang</i> (Chicago), <i>Antonio Boveia</i> (Ohio State)

- **Monte Carlo Task Force and Production Team:** coordinated by *John Stupak* (U. Oklahoma)
 - 1) Assess the MC needs \Rightarrow “Task force” (work completed)
 - 2) Produce MC samples \Rightarrow “Production Team” (ongoing)

Topical Group Activities

- General [Energy Frontier Wiki](#)
- **Electroweak TGs**
 - EF01, EF02, EF03, EF04
- **QCD and Strong Interaction TGs**
 - EF05, EF06, EF07
- **BSM TGs**
 - EF08, EF09, EF10



Multiple Ongoing Activities

- See Topical Group [Wiki pages](#) and [indico meeting agendas](#) for details of ongoing activities
- [EF calendar](#) and [communications](#)

The Energy Frontier Group (II)

BNL Leadership

- **Liaisons:** high-level and bi-directional communication b/w Frontiers

Other Frontier	Liaisons
Neutrino Physics Frontier	André de Gouvêa (Northwestern)
Rare Processes and Precision	Manuel Franco Sevilla (Maryland)
Cosmic Frontier	Caterina Doglioni (Lund), Antonio Boveia (Ohio State)
Theory Frontier	Laura Reina (FSU)
Accelerator Frontier	Dmitri Denisov (BNL), Meenakshi Narain (Brown)
Computational Frontier	Daniel Elvira (FNAL)
Instrumentation Frontier	Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay)
Community Engagement Frontier	Daniel Whiteson (UCI), Sergei Gleyzer (Alabama)

- Renew interest in Snowmass community for Muon Collider:
Muon Collider Forum established with *Accelerator and Theory Frontiers* → [Wiki \(new\)](#)

Muon Collider Forum Coordinators

EF: **Kevin Black** (U. Wisconsin-Madison), **Sergo Jindariani** (Fermilab)
AF: **Derun Li** (LBNL), **Diktys Stratakis** (Fermilab)
TF: **Patrick Meade** (Stony Brook U.), **Fabio Maltoni** (Louvain U., Bologna)

The Energy Frontier Group (III)

- **Snowmass thrives on the participation of Early Career (EC) physicists and offers an ideal environment for young people to get involved and promote their own initiatives**

Early Career Representatives

- **Grace Cummings** (U. Virginia) - gec8mf@virginia.edu
- **Matt LeBlanc** (U. Arizona) - matt.leblanc@cern.ch

- EC leadership is for a 3-month term (staggered): Grace and Matt are current EF representatives
- Get in touch especially if you want to get involved in EF activities, but need guidance how to do it effectively: Grace and Matt will help build bridges between projects and new collaborators

Additional Snowmass resources for Early Careers:

- [#snowmass-young](#) and [#welcome-to-snowmass](#) as points of entry for newcomers
- The [Snowmass Early Career](#) twiki, which includes a description of our structure, current leadership, and the SEC calendar of all events.

LOIs and Contributed Papers

- **Broad effort of LOI solicitation through dedicated Topical Group meetings**
 - 376 received - see list [here](#)
 - 268 have EF as primary
 - **Cross-frontier LOIs:** TF (21), AF (20), IF(17), RF (16), CF (14), NF (11), CompF (9)
- **LOIs have contributed to shaping Topical Group activities**
 - see breakout sessions of the [Community Planning Meeting \(CPM\), Oct 5-8, 2020](#)

New

❖ **List of Expected Contributed Papers (*work-in-progress*):**

https://docs.google.com/spreadsheets/d/e/2PACX-1vSoMhW5FiyD_0DVN1zau9ttAI4LDdT3NFqDZpplTO_5u-ULXWLRcMULYcPCbVFbQ5IHapLpz5T5dGcS/pubhtml?gid=1225382680&single=true

- **If you haven't submitted a LOI, or you are not in the above list of planned papers, you can still contribute! just get in touch with your ideas and plans**

Timeline and Activities

1/21-6/21	30/6/21	12/7/21	30/8/21	24/9/21	15/3/22	31/5/22	30/6/22	17-26/7/22	30/9/22	31/10/22
Activity Slowdown	Restart of Activities	DPF Meeting + Snowmass Townhall	EF restart Workshop	Snowmass day	Deadline Contributed Paper Submission	Prelim. TG Reports	Prelim. Frontier Reports	Community Summer Study (UW-Seattle)	Final Reports	Snowmass Book & ArXiv docs

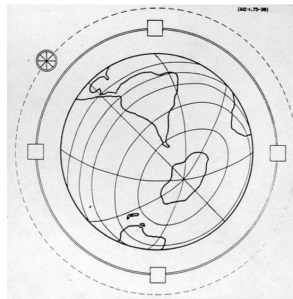
Future EF Events:

- **Regular EF Topical Group meetings**, on a bi-weekly/monthly basis
- **Snowmass Agora on Future Colliders**, once a month
- **Winter 2021-2022: few one-day virtual EF workshops by topic (SM, Higgs, BSM, Colliders,...)**
 - Check progress towards March deadline for contributed papers, discuss overlap with other frontiers
- **28 March – 1 April 2022 at Brown Univ: EF workshop to review contributed papers**
 - Focus on main themes and messages by contributed papers, towards May deadline for TG reports.
- **April-July 2022: drafting and circulations of prelim. TG and EF reports, then public readings**
- **17-26 July 2022 in UW-Seattle: Community Summer Study, see [web page](#)**
 - Hybrid meeting with 700 expected in-person participants, 10 days, similar format as in Snowmass 2013
 - Goals: Build community consensus, Cross-group collaborations, Report final preparation, Preparing the main messages for the P5 hand off

Summary

- The Future of the Energy Frontier is in our hands → let's build a coherent vision for the future
- Ambitious Energy Frontier plans to pave the way towards addressing big questions
- Cross-fertilization across fields (Theory, Cosmics, Accelerators, Instrumentation etc.)
- Energy Frontier activities have taken off in 2020, and restarted in Summer at full steam
- *The 2020 EF organization carries on, Strategic plans have been laid out, Connection with other frontiers is established, Early Career representation is active, Monte Carlo sample production has started, Studies are on-going*
- **Plenty of time to join activities, propose new studies and address the many open questions**

Let's collectively **DREAM BIG!**



*E. Fermi (1954, APS)
The Globatron: 5000 TeV collider,
Cost: 170B USD,
to be built by 1994*

Backup

The Snowmass Process

Recurring long-term planning exercise for the US particle-physics community

- “Develop community long-term physics aspirations.”
- “Communicate opportunities for discovery in particle-physics to broader community and to the (US) government.” (Young-Kee Kim, former DPF Chair, [Town-Hall Meeting, 2020 April APS meeting](#))

Physics-driven effort

- Covers all areas of particle physics and facilitates cross-cutting.
- Develop overarching physics studies.

Global effort

- An opportunity for the entire HEP community to define the most important questions for our field and identify promising directions to address these questions in a global context
- Input from non-US community is essential
- Input from recent international studies, e.g. HL-LHC, European strategy (see report, July 2020), future colliders communities etc.

Big Picture Questions

- Why is physics at the energy frontier important?
- *How should the US be involved in near future and far future energy-frontier machines after HL-LHC?*
- What could be the energy-frontier machines that follow the HL-LHC?
- *How can the US continue to play a leadership role in energy-frontier experiments?*
- *How can the Snowmass process help develop a plan for the energy-frontier research and convince the community about our priorities?*
- *Should we start entertaining the idea of a future collider in the US again? If so, what are our goals, the benefits for the US and the international community, and how can we get there?*
- etc...

- Energy Frontier Kick-off Meeting on May 21, 2020, [see agenda](#)
- These questions were discussed in the Panel: **“The importance of the Energy Frontier in the US HEP future planning”** at the [“Energy Frontier Workshop - Open Questions and New Ideas”, July 20-22, 2020](#)
 - By Jorgen D'Hondt, Nima Arkani-Hamed, Sarah Eno, Vladimir Shiltsev, Xinchou Lou, Young-Kee Kim
 - See [Zoom recording of Panel Discussion](#)

Topical Group Activities

EW Topical Groups

EF02 - Higgs boson as a portal to new physics

- 1) Higgs as origin of EWSB, naturalness/fine-tuning portal to new physics, 2) Higgs and flavor, 3) Higgs and EW phase transition.
 - a. BSM Higgs: 2HDM, SUSY Higgs ($A \rightarrow Z h$, LFV, Charged Higgs etc.), extra scalars, exotic decays, mono-Higgs searches
 - b. **Composite Higgs (with BSM groups)**
 - c. **Effect on Higgs couplings to fermions/bosons and Higgs width from extending the scalar sector**
 - d. **Flavor violating Higgs production and decays**
 - e. $H \rightarrow hh$

• **Higgs rare decays**

EF01 - Higgs boson properties and couplings

- Higgs mass and width
- Higgs couplings to SM gauge bosons and fermions
- Higgs production modes: inclusive and diff. measurements (incl. $t\bar{t}H$)
- HH production (includes resonant production)
- Higgs self-coupling
- **Anomalous couplings (including CP violation)**
- **Inputs to the GlobalFit**

EF04 - Precision physics and constraining new phys.

- Precision fits of SM observables
- Multi-boson signatures, and VBF, VBS processes
- (SM)EFT analyses of EWPO, Higgs, and top observables
- Correlations among exp. and theory uncert.,
- Modeling of EW and QCD uncert., and their combination

EF03 - Heavy flavor and top quark physics

- Heavy flavor production (top, bottom, and charm)
- Top-quark properties (mass, couplings) and diff. measurements
- New top-quark production modes and rare decays
- Detection algorithms for top-quark identification

Topical Group Activities

QCD Topical Groups

EF07 - Heavy Ions

- Physics of heavy ions (HI) and its impact on EF
- Physics at electron-ion colliders
 - a. **EW physics in HI (with EW groups)**
 - b. **BSM Searches in HI (with BSM groups)**
 - c. **Jets in HI**

EF05 - Precision QCD

- Jet and jet substructure
- Higher-order effects and impact on precision QCD physics
- Strong coupling constant and its running
- Quark masses
- W/Z(+jets) boson production
- Accuracy of future MC event generators
- **Impact of PDF fits and PDF-sensitive measurements**

EF06 - Hadronic structure and forward QCD

- PDF Fits and Generalized PDF
- Hadronic structure
- Forward and soft QCD
- **Hadron spectroscopy (with RF)**

Topical Group Activities

BSM Topical Groups

EF08 - Model Specific explorations

- SUSY, Extra Dimensions, and Leptoquarks etc.
- Sensitivity, Reinterpretations of sensitivities (e.g. a long-lived particle as a Higgsino)
- Model parameter scans and comparisons with precision measurements (e.g. pMSSM scans)
 - a. SUSY: Strong (inclusive searches / gluino / squark), 3rd gen (stop, sbottom), EWKino, singlino, "Pure" higgsino, R-parity violating SUSY
 - b. Blackhole Multijets, RS Gravitons
 - c. pMSSM or other scans
 - d. **Model-specific searches for excited fermions**

EF10 - Dark Matter at colliders

- Dark Matter and Dark Sector searches at EF colliders
- WIMP models: ew multiplet, vector/scalar mediator simplified models, and Higgs portal
- Models targeting different DM masses and couplings wrt WIMP, and portals through dark photon and generic dark scalar/pseudoscalar
- DM interpretation of searches for visible decays of mediators
- **Complementarity with fixed target, direct detection (with CF & RF)**
- **Projections for FASER/CODEX-b/Mathusla, etc. (with RF)**
- **H/Z/top/mesons rare decays etc. (with EW groups)**
- **mono-X searches, MET Signatures**

EF09 - More General explorations

- New Fermions (Top partners, Excited Quarks/Leptons, Sterile Neutrinos etc.)
- New Bosons (W' , Z' , diboson-resonances etc.)
- Dark/Hidden sectors (ALP, dark photons etc.)
- **BSM interplay with EFT (with EF04)**